Estimation of cyclic error due to scattering in the internal OPD metrology of the Space Interferometry Mission

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Abstract: A common-path laser heterodyne interferometer capable of measuring the internal OPD with accuracy of the order of 10 picometers was demonstrated at JPL. To achieve this accuracy, the relative power received by the detector that is contributed by the scattering of light at the optical surfaces should be less than -97 dB. A method has been developed to estimate the cyclic error caused by the scattering of the optical surfaces. The result of the analysis is presented.

Key words: Metrology, scattering, cyclic error

1 Introduction

The Space Interferometry mission (SIM) is a space-based optical Michelson interferometer. Its primary goal is to measure the positions and motions of celestial object. In its simplest form, SIM performs relative astrometry between two stars by taking a pair of internal optical path delay measurements: one for each star. The two delay-line positions are determined by searching for the maximum fringe amplitude on each star. A key measured quantity is the change in internal delay Δd,

$$\Delta d = \vec{B} \bullet (\vec{s}_1 - \vec{s}_2),$$

where $\vec{B}$ is the baseline vector and $\vec{s}_1$ and $\vec{s}_2$ are unit vectors to the two stars. The angular distance between the two stars $(\vec{s}_1 - \vec{s}_2)$ can then be calculated once Δd and $\vec{B}$ are known. The function of internal metrology is to measure Δd. The baseline of SIM is 10 meters; Δd must be measured with accuracy on the order of 10 picometers to achieve 1 micro arcsecond astrometry.

A Common-Path Heterodyne Interferometer (COPHI) was proposed at JPL as a multi-purpose and high-resolution distance measuring interferometer.[2-4] A similar scheme as shown in Figure 1 was proposed and adapted by SIM for the internal metrology of optical path difference (OPD) in the two arms of the stellar interferometer. The measurement beam (with frequency f_0) is split by the astrometric beam combiner into two beams. The beams propagate towards the star in the two arms of the stellar interferometer. Two masks are placed after the beam combiner to spatially separate the two beams, one with two rectangular apertures in the south-north orientation and the other with two rectangles in the east-west orientation. The two beams are retro-reflected by corner cubes #1 and #2. A second laser beam with frequency $f_0+\Delta f$, which serves as the local oscillator, then interferes with both measurement beams at the second beam splitter. The heterodyne signals are detected by the two detectors, respectively. The phase difference ($\Delta\phi$) between the two heterodyne signals is used to calculate the displacement of optical path between the corner cubes:

$$\Delta d = \frac{\Delta\phi}{2\pi}\frac{\lambda}{2},$$

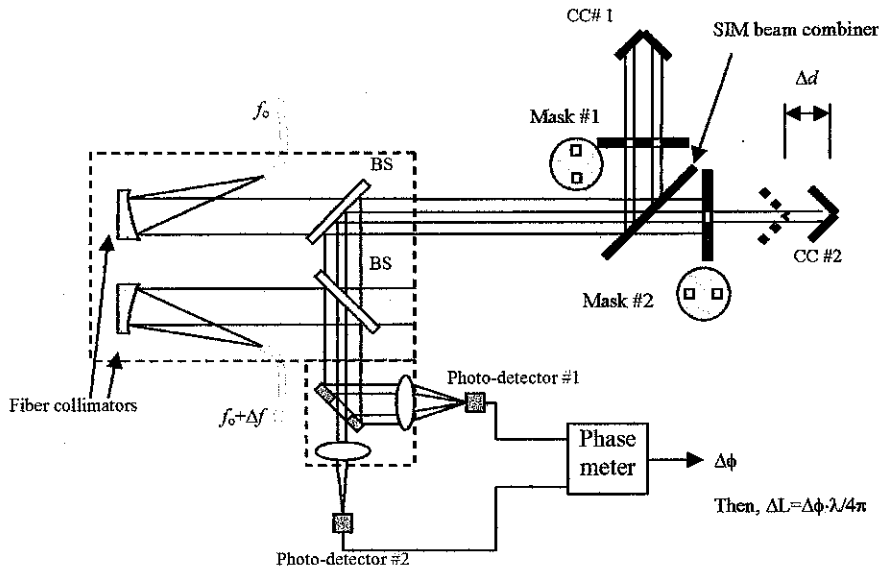

Figure 1. The layout of COPHI configured for the metrology of internal OPD in SIM.

where λ is the wavelength of the metrology laser.

2 Cyclic errors

There are two types of cross-talk in the measurement of the displacements in the two arms. Cross-talks manifest as cyclic errors in the measurements, which are errors with the same or multiples of the signal frequency as the delay (Δd) in the arms change. The first type is called the inter-arm cross-talk. Because of diffraction and scattering, light in first arm crosses over to the collection aperture of the detector for the second arm or vice verse. The second type is called the intra-arm cross-talk. It is due to scattering and multiple reflections in one arm. A small amount of light power from scattering or multiple reflections is received by the detector of the same arm. The measurement error in distance x for both types of cross-talk is proportional to the relative amplitude of the electric field of the light collected by the detector. It is given as[5]

$$|dx| = \frac{\lambda}{4\pi}\left|\frac{dA}{A}\right| = \frac{\lambda}{4\pi}\sqrt{\left|\frac{dP}{P}\right|},$$

where A is the amplitude of the electric field and P is the power of the light received at the detector while dA and dP are that of the cross-talk received by the detector. For a cyclic error of 2 picometers the relative power of scattered light is -97 dB.

The inter-arm cross-talk can not be reduced by the technique known as in-phase cyclic-averaging. Thus it must be small by design. Extensive modeling of diffraction effects has been carried out and optimization of the masks has been performed at JPL to minimize the cross-talk of diffraction to be < 1 picometer.[6] The intra-arm cross-talk, however, can be reduced by cyclic-averaging. This means that the requirements on the intra-arm cross-talk do not have to be as tight as the inter-arm case, but still less than tens of picometers. We present here the results of modeling the cross-talk due to scattering.

Harvey characterized the scattering of optical surfaces in great detail.[7] His result, often referred as the Harvey model, is widely used in modeling the scattering of light by optical surfaces. The optical analysis software, ASAP, utilizes the property of Harvey model.[8] It also has a versatile physical optics tool for coherent beam propagation.[9]

We have built a model of the metrology optical system in ASAP, as shown in Figure 2. Laser light from the fiber is propagated to all the optical surfaces where the light is scattered with the full coherent power factored into the calculation. We have determined that inter-arm cross-talk due to scattering is less than -110 dB, i.e. much less than 1 picometer cyclic error. On the other hand, scattering is the main contributor of the intra-arm cross-talk. There are three major contributors: 1) scattering of the three surfaces of the corner cube; 2) scattering by the fiber tip of returned light and received by the detector after another round trip; 3) scattering by the detector and received by the detector after another round trip. In addition to providing the estimation of the cyclic error of the metrology system, scattering analysis also assists us in our decision to choose the specification of surface finish for our optics. For example, if we specify the micro roughness of the key surfaces to be 5 Angstroms RMS, the relative power for cases 1 and 2 are -85 dB and -110 dB. For case 3, the relative power from the scattering of the detector is -85 dB for normal incidence. If we tilt the detector, the relative power from scattering can be reduced significantly, as illustrated in Figure 3. The reflectance of the detector is assumed to be 2% and the RMS roughness is 5 Angstroms. It appears that the cyclic error due to the scattering of the corner cube is greater than -97 dB, which is required to achieve less than 2 pm error. Additional reduction in cyclic error can be achieved by cyclic averaging.

In summary, A model is built in ASAP for the SIM internal metrology optical system. Scattering analysis is performed to assist our design and development of our metrology system. Our analysis shows that the cyclic errors due to scattering of key optical surfaces are near the acceptable levels if we use surfaces better than 5 Angstroms RMS micro roughness.

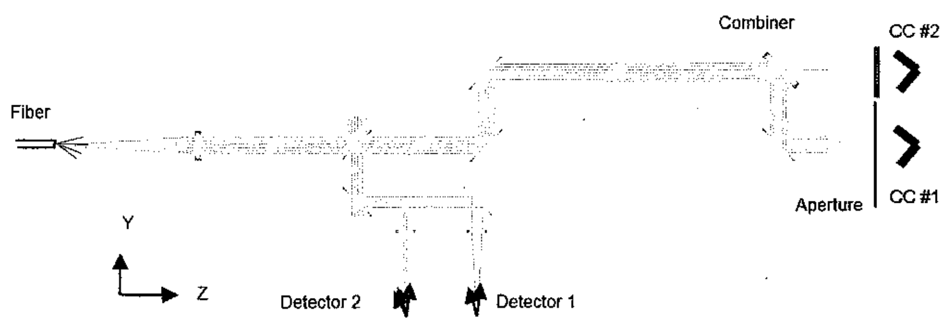

Figure 2. Optical lauout in ASAP of the metrology system.

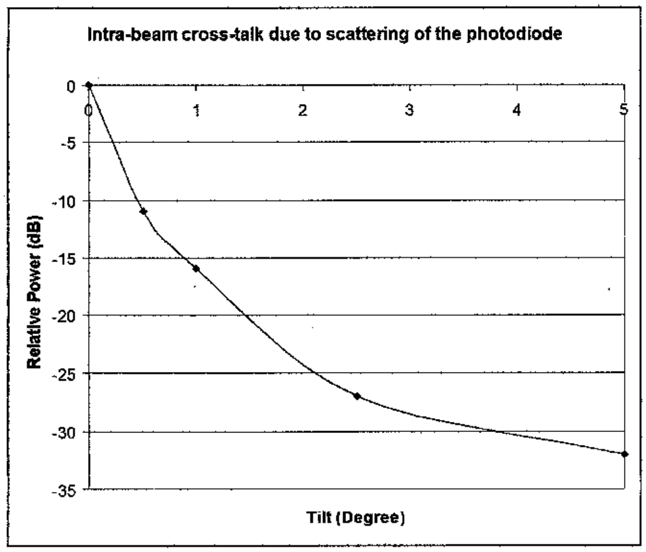

Figure 3. Relative power to that of normal incidence of light scattered by the detector received by the detector after another round-trip.

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